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Single step links of the superdeformed band in ^{194}Pb: a measure of the absolute excitation energy, spin and parity of the superdeformed states

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Abstract

The EUROGAM array has been used to investigate the decay out of the yrast superdeformed (SD) band in ^{194}Pb. Six single step decays from the lowest observed SD states to low-lying states at normal deformation (ND) have been identified. From this observation, the excitation energy of the SD band in ^{194}Pb is established at 4877 ± 1.5 keV for the 6^+ SD state. The most probable spins and parities of all members of the SD band are also deduced assuming that the SD states have even spin and positive parity.

The observation of superdeformed (SD) nuclei in the mass 150, 190, 130 and 80 regions has stimulated a wealth of theoretical interpretations [1–3] and experimental investigations [4,5]. A common feature of all the SD bands is their sudden depopulation at low rotational frequency and, except for a few cases [6–8], the non-observation of the discrete linking transitions between the SD states and the low-lying states at normal deformation (ND). Finding these missing linking transitions is a major motivation of experiments today because it is the only way one can measure the most fundamental properties of the SD nucleus, namely the excitation energy, spin and parity of the SD states. These are the quantities which provide a stringent test

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for theoretical models.

It has been predicted [9], and recently experimentally established [10], that the decay from the SD states involves a statistical mixing of the SD states with the neighbouring ND states. Thus, the SD decay spectrum reflects the statistical decay of the admixed ND states which lie at high excitation energy in the first well [10–12]. The spectrum comprises a quasi-continuous distribution of transitions and, in addition, sharp lines whose strength distribution are very probably subject to Porter-Thomas fluctuations [13]. In the ^{194}Hg nucleus, primary high-energy transitions have been observed at the very end of the decay spectrum [8] (the primary γ-rays are defined as the high-energy first-step transitions from the SD levels). These transitions pin down the excitation energies, spins and probable parities of the SD band. The 10^+ and 12^+ states have been determined to lie at 4204.8 keV and 4407.4 keV above the normal deformed yrast states of the same spins.

The present work is devoted to the study of the deexcitation of the yrast SD band in ^{194}Pb, a subject already addressed by several authors [14–16]. Lead isotopes have been extensively studied [17,18]. Near the ground state, there is a closed proton shell. Therefore, the level density in their first well is reduced. In ^{194}Pb, the yrast SD band head is predicted at 4.86 MeV excitation energy at spin zero [1], which is much lower than the value of 6 MeV extrapolated from measurements in ^{194}Hg [8]. If indeed, the excitation energy is lower, it would reduce the number of possible pathways through which the decay of the SD band may proceed. In fact, a comparison of the general features and fluctuation properties of the decay spectra from ^{192}Hg and ^{194}Pb has shown that the decay out is less fragmented in ^{194}Pb [19], leading to stronger high-energy discrete transitions. All these reasons make ^{194}Pb one of the best candidates to search for the discrete transitions deexciting the SD band, and to establish the excitation energy, spin and parity of the SD states.

Excited states in ^{194}Pb were populated in the ^{184}W (^{16}O, 6n) fusion-evaporation reaction at a beam energy of 113 MeV. The beam was provided by the Vivitron accelerator of the C.R.N. Strasbourg. The targets consisted of two stacked 325 μg/cm^2 enriched ^{184}W deposited on a 10 μg/cm^2 carbon backing. The γ-rays emitted by the ^{194}Pb nuclei were detected with the EUROGAM array [20] which consists of a total of 54 Compton-suppressed germanium (Ge) detectors. Thirty of these detectors are 73% efficiency coaxial Ge located in the forward and backward hemispheres, and 24 are clover detectors located in two rings near 90 degrees relative to the beam direction [21]. Events were recorded with the requirement that at least 6 unsuppressed Ge detectors fired in prompt coincidence. A total of 10^9 triple and higher-fold events were collected in the experiment; quadruple and quintuple events represented 31% and 19% of the events respectively.

There was no backing to stop the recoiling ^{194}Pb nuclei. Therefore, the SD transitions were emitted in flight. Making use of the selectivity of the high-fold data, triple SD gated spectra were produced at all available angles in order to determine the fractional Doppler shift of the SD transitions. The SD nucleus velocity at the point of decay was measured to be 84% of the initial speed, 0.0095c, of the residual nucleus. A typical background subtracted triple SD gated spectrum is shown in Figs. 1a–c. The γ-ray energies stored in this spectrum are those of transitions in coincidence with at least 3 SD lines out of those labelled g in the figure. Besides known lines in the ND level scheme (labelled with their energies in Figs. 1a–b), additional new lines are observed in coincidence with both the SD band and the low-lying transitions at normal deformation. Their energies range from a few hundred keV to 3.34 MeV. Among them, the high energy lines at 2348, 2439, 2579, 2636, 2742 and 2806 keV are our main candidates for the linking transitions. These do not correspond to strong contamination lines in the reaction as seen in the total projection spectrum shown in Fig. 1d. Although the intraband intensities show that 52% and 42% of the decay out of the SD band occurs from the $I^\pi = 6^+$ and $I^\pi = 8^+$ SD levels respectively, only a small fraction of the SD flow is carried by the observed primary γ-rays. We obtain only $\approx$ 10% of the total SD band intensity by integrating all the intensities of the decay lines given above. This is consistent with the statistical decay scenario in which the main part of the decay should proceed via a continuum of transitions as seen in the $^{192-194}$Hg nuclei [8,10–12]. No discrete lines populating the $2^+{}_2$ state at 1309 keV have been found yet, which indicates that this state is fed by several multiple steps decays.

Contrary to the case of ^{194}Hg, where only negative parity states are populated by the high-energy pri-

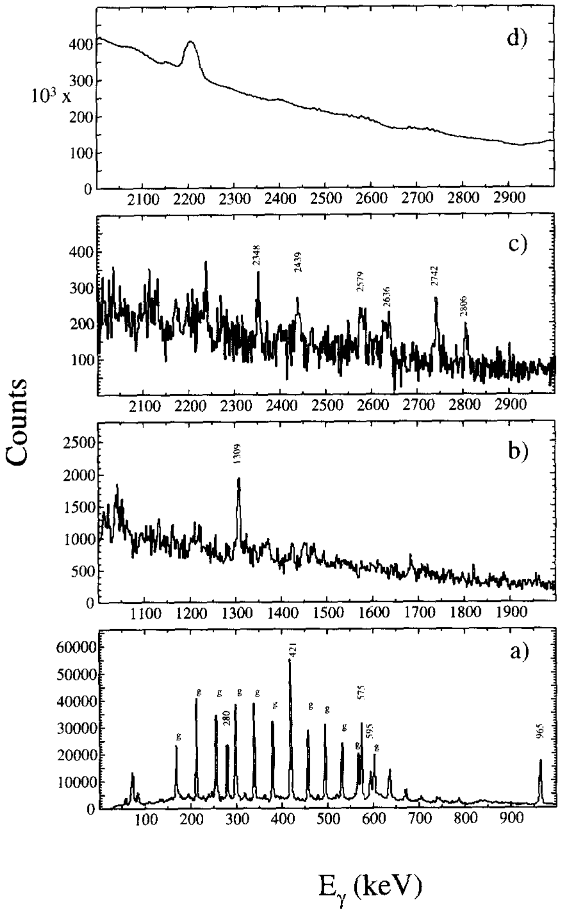

Fig. 1. (a–c) Background subtracted triple SD gated spectrum of the yrast SD band of ^{194}Pb showing the high energy transitions directly connecting the SD and the ND levels. The background is a fraction of the corresponding double SD gated spectrum. The gates are labelled g in the figure. (d) For comparison, the total projection of all the events collected in the experiment is shown in the 2000–3000 keV energy range.

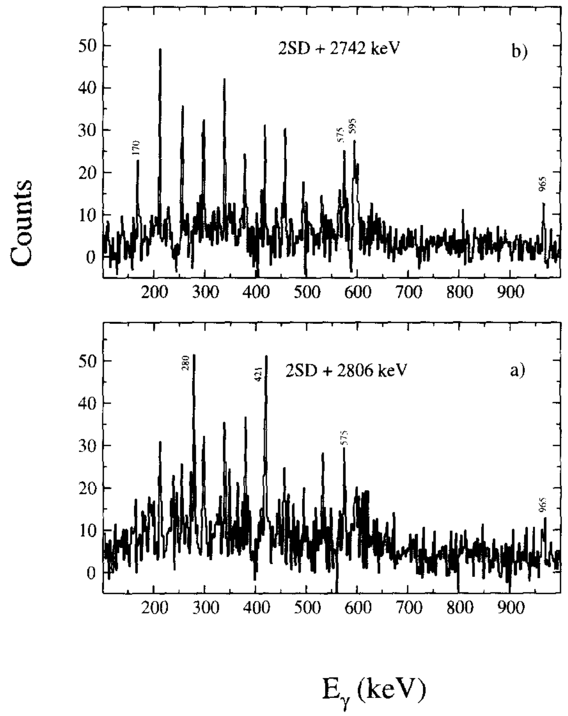

Fig. 2. Examples of background subtracted triple gated spectra on any pair of two SD transitions out of those labelled g on Fig. 1a and the indicated one-step decay lines. The peaks labelled with their energy correspond to the known yrast lines in the level scheme of ^{194}Pb at normal deformation.

mary transitions, our data show that both negative and positive parity states are fed by the one-step decays in ^{194}Pb. Their coincidence relationships have been established although, many of the lines are probably doublets or triplets, as can be seen in Fig. 1c. Two examples of the spectra obtained by setting two gates on any SD lines (labelled g in Fig. 1a) and one gate on the 2806 keV or the 2742 keV lines are shown in Fig. 2. The 170 keV SD band member is clearly in coincidence with the 2742 keV transition, while it is not in coincidence with the 2806 keV line. We also see different transitions in the first well (labelled with their energies in the figure) in coincidence with these candidates, which allows us to firmly establish the level scheme. The 280 keV ($5^- \to 4^+$) is clearly visible in Fig. 2a in coincidence with the 2806 keV line, while the 595 keV ($6^+ \to 4^+$) line is not present. The 419 keV line is stronger and broader than the other SD lines. This means that the 421 keV ($7^- \to 5^-$) is also populated by the 2806 keV transition. No evidence of a coincidence between the 2806 keV line and the 166 keV ($9^- \to 7^-$) yrast line is found. In Fig. 2b, only the 595 keV ($6^+ \to 4^+$), 575 keV ($4^+ \to 2^+$) and 965 keV ($2^+ \to 0^+$) transitions are found to be in coincidence with the 2742 keV line. From these observations, we deduce that the 2742 keV transition populates the yrast state at 2135 keV and links the 6^+ SD state to the 6^+ ND state, while the 2806 keV line populates the 2241 keV state and thus links the 8^+ SD state to the 7^- state at normal deformation. A 2746 keV transition has already been suggested as a linking transition in ^{194}Pb [16] however, its location

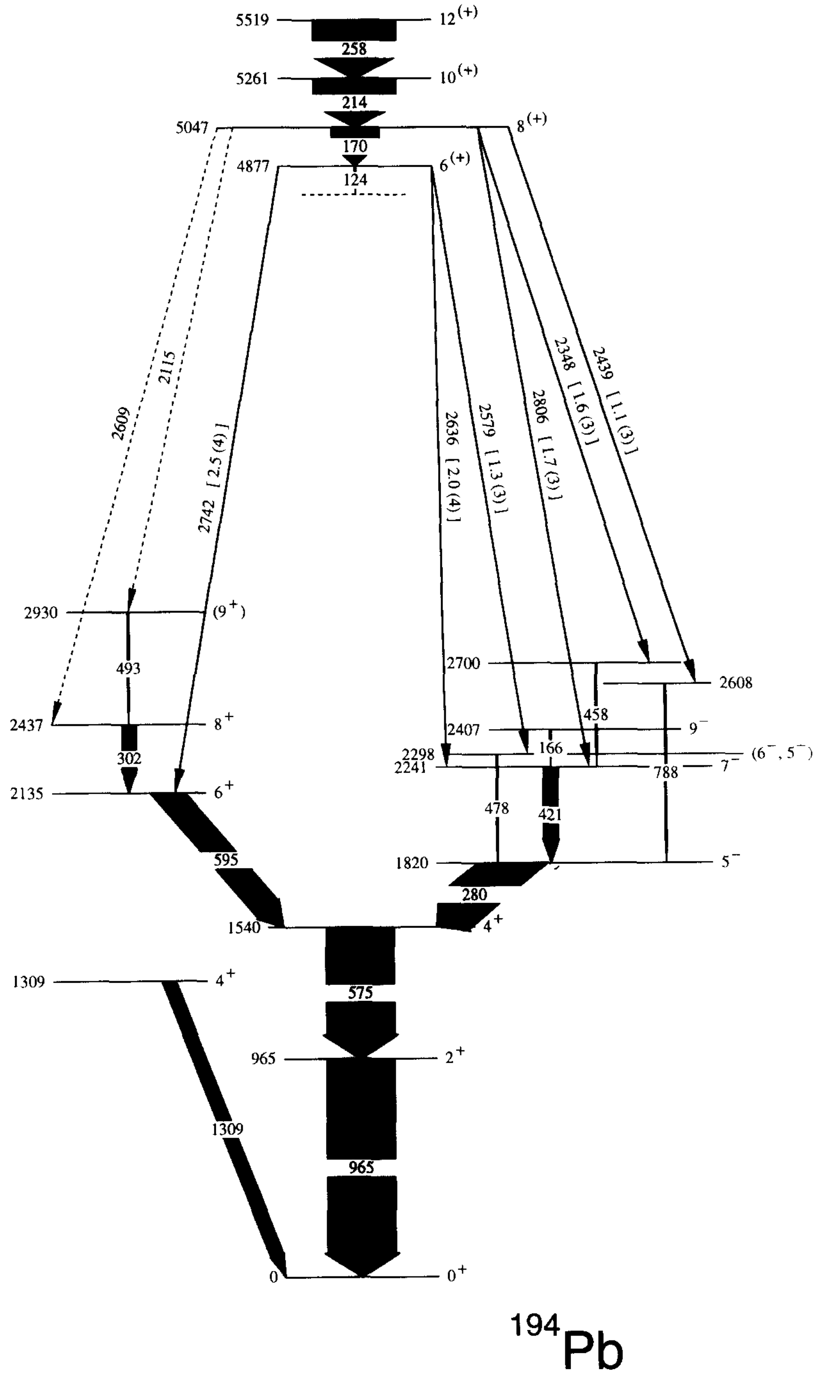

Fig. 3. Partial decay scheme of the yrast SD band in ^{194}Pb. The precision on the new transitions and on the SD states energies is of the order of 1.5 keV. The intensities of the linking transitions are indicated in brackets (in % of the SD band intensity). The dashed arrows indicate tentative emplacements for the transitions.

in the level scheme was tentative.

From all our coincidence relationships, we have built the partial level scheme proposed in Fig. 3 for the deexcitation of the SD band in ^{194}Pb. It is worth noting that the new yrare levels proposed at 2298 keV and 2608 keV excitation energy have not been reported in the deexcitation of higher-lying ND states produced in heavy-ions fusion reactions [18] but have been suggested in the study of the ^{194}Pb nucleus produced in the beta decay of ^{194}Bi [22].

The absolute excitation energy of the SD band is determined in the ^{194}Pb nucleus for the first time: the 6^+ level lies at 4877 ± 1.5 keV above the 0^+ ND ground state and at 2742 ± 1.5 keV above the ND yrast 6^+ level. We are also able to propose spins and parities for these levels based on the following arguments.

A weak 478 keV M1 transition (0.8% of the intensity of the 965 keV $2^+ \to 0^+$ transition) has been reported but not placed in the level scheme by P. van Duppen et al. in the study of the beta decay of ^{194}Bi [22]. In our data, a 2579 keV transition is in coincidence with all the SD band members, with the 280 keV $5^- \to 4^+$ yrast line as well as with a line at 478 keV. This line which we assume to be the previously reported one, would deexcite a new 6^- or 5^- level at 2298 keV excitation energy and therefore the spin and parity of the SD states are severely constrained. The ground band in the SD well of an even–even nucleus is expected to have even spin and positive parity, particularly when pairing correlations are present. In this case, the SD state at 4877 keV can only have spin 6. If one considers, for example, the possibility of a spin 8^+ for this state (a spin 4 would imply $\Delta I = 3$ transitions!) then the 2579 keV transition would be of magnetic quadrupole M2 nature and the 2806 keV transition would have an E3 character. Transitions of such high multipolarity are very improbable. If odd spin and negative parity were to be considered, 7^- would be a possible assignment for the 4877 keV SD state.

The transition strengths have been obtained for the decay transitions under the reasonable assumption of a dipole nature (it was not possible with the available statistics to measure their angular distributions). Assuming a constant quadrupole moment of 20 eb for the SD band [23], the lifetimes of the 8^+ and 6^+ SD levels can be obtained. From the branching ratios of the primary transitions, transition strengths ranging from 10^{-8} to 5×10^{-8} W.u. and from 1.5×10^{-6} to 5.3×10^{-6} W.u. have been obtained assuming E1 and M1 transitions respectively. These represent highly retarded transitions and indicate very small mixing between ND states and SD states at the point of decay. The ratio of the calculated statistical E1 lifetime (using a standard γ strength function based on the giant dipole resonance) to the measured E1 partial lifetime, provides a measure of the squared amplitude α^2 of the SD wavefunction in the ND well. α^2 is of the order of 0.2% and 0.5% for the 8^+ and 6^+ SD states. The measured SD excitation energies constitute a very sensitive test of the different theoretical models and prescriptions available for the description of SD nuclei. The theoretical expectations of Krieger et al. in static HF + BCS calculations using the SkM* effective force (4.86 MeV excitation energy for the 0^+ SD state in ^{194}Pb) [1] are in good agreement with the extrapolated value of 4.6 MeV obtained in this work. However, the same calculations give an excitation energy which is too low in the ^{194}Hg case (5 MeV vs. 6 MeV for the spin zero levels).

The excitation energy of the 6^+ SD level in ^{194}Pb is only 2742 keV above the 6^+ ND yrast level. With the expected low density of ND states, it is not clear that a ND state at this excitation energy will be very complex (i.e., a compound state). Thus, its decay may not be truly statistical and may be partially governed by the nuclear structure of the initial and final states. This might explain why the strongest of the single-steps (2742 keV line) is of probable M1 nature, whereas transitions of E1 multipolarity are strongly favoured in a purely statistical decay.

In summary, we have measured the excitation energy and most probable spins and parities of the yrast SD states in ^{194}Pb by finding 8 single-step decays to the ND states. A good agreement is found between the predicted and the measured values of the excitation energy for this nucleus. With powerful arrays such as EUROGAM and GAMMASPHERE, the excitation energy of the SD bands are being measured for the first time. Reproducing all the results constitutes a new challenge for SD nuclei theories and models.

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